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Effects of secondary succession and afforestation practices on soil properties after cropland abandonment in humid Mediterranean mountain areas

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ABSTRACT

Cropland abandonment and subsequent revegetation processes (due to secondary succession and afforestation practices) are global issues with important implications in Mediterranean mountain areas. Several publications have reviewed the impact of cropland abandonment and revegetation on the soil properties dynamics but, so far, limited attention has been paid to Mediterranean humid mountain areas. This paper examines six neighbouring land covers, in the Central Spanish Pyrenees to determine the effects of land covers, cropland abandonment and consequently secondary succession and afforestation practices on soil properties. For this purpose, a total of 85 samples from 6 land covers and from two soil depths were analysed. We observed that changes in soil properties after cropland abandonment were limited, even if afforestation practices were carried out, and no differences were observed between natural succession and afforestation. Land cover and depth had a significant effect on the physical and chemical variables, being larger in the uppermost 0–10 cm depth. The organic and inorganic carbon and N concentration, SOC and TN stocks, CN ratio, organic matter, and bulk density showed significant differences. Afforestation improved soil properties, aggregate stability and carbon concentration and stocks when compared to neighbouring bare soils. A soil quality index –based on statistical analysis-suggested that natural forests and *Pinus nigra* areas developed a higher soil quality rating. Our general results also demonstrated that the impact of disturbance by afforestation techniques (microsites) is difficult to discern. The differences found with respect to the native forest appear to indicate that the afforested soils have not yet reached their maximum soil quality and maximum potential as soil organic carbon sink. As there was no difference found between the soil improvement by natural succession in comparison to afforestation, these results put the question forward which type of forest and landscape management is most appropriate to decide for the best practices after cropland abandonment for soil recovery and erosion control.

1. Introduction

Most Mediterranean mountain areas have been subjected to significant human pressure through deforestation, cultivation of steep slopes, fires and overgrazing (Roberts, 2014). During the 20th century the mountainous areas of the northern rim of the Mediterranean region were affected by rapid population migration and abandonment of cultivated fields (MacDonald et al., 2000; Keenleyside and Tucker, 2010). Cropland abandonment is one of the main changes in land cover in Mediterranean countries leading to the expansion of forest and scrublands (Tasser et al., 2007; Sluis et al., 2014). These abandoned areas can be left to undergo secondary succession (passive restoration) or be subjected to active restoration that mostly consists of tree (i.e. conifers) and shrub planting (i.e. *Quercus coccifera*, *Atriplex halimus*) (afforestation), resulting in a mosaic of regenerated vegetation and afforestations.

Abandoned Mediterranean cropland under secondary succession is initially colonized by herbaceous vegetation which persist for a long time before woody vegetation establishes (Bonet and Pausas, 2004). Molinillo et al. (1997); Nadal-Romero et al. (2013)

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identified different succession stages: (i) during the first years an invasion by herbaceous plants occurs; (ii) between 10 and 60 years of abandonment generalized cover by woody shrubs is observed; (iii) around 60 years of abandonment the entry of young trees in field is common; and (iv) more than 100 years are necessary to observe a forest stage (Lasanta et al., 2005). In that sense, Errea et al. (2015) corroborated that only 10.6% of abandoned lands in the Aísa Valley (Central Pyrenees) had already reached a forest stage after more than 50 years of abandonment.

Due to the slow process of secondary succession, and with productive (to achieve self-sufficiency in the supply of pulp and paper) and environmental objectives (to control hydrological and geomorphic processes in order to reduce flood frequency and magnitude and soil erosion), extensive afforestation programs were conducted by national forest services all over the Mediterranean region (Ortigosa et al., 1990; Yaşar Korkanç, 2014). Afforestation is defined as establishment of forests on lands which historically have not contained forests (Houghton et al., 1996) or alternatively as lands which have been without forest for a period of several decades and have previously been under a different land use (Watson et al., 2000). The case of Spain is a good example: modern afforestation policies were introduced in 1940 by the Forest Administration in the Pyrenees, Galicia, the Alicante Region, Iberian Range, Baetics Range and the northwest of the Murcia Region (Calvo-Iglesias et al., 2009; Symeonakis et al., 2007). Afforestation has been based mainly on conifers because they are fast-growing species, and also because it was believed that this would lead to rapid restoration of soil hydrological processes, to control soil erosion, to regenerate forest ecosystem services and the formation of protective vegetation cover (Ortigosa et al., 1990). In the case of the Pyrenees, large areas were afforested with *Pinus nigra* and *Pinus sylvestris* (Ortigosa et al., 1990). Both processes, secondary succession and afforestation, resulted in the expansion of shrublands and forests, and as a result of both processes, the fraction of forest cover in the EU-Mediterranean countries is increasing.

Cropland abandonment and the revegetation process have been extensively examined from a hydro-geomorphological (García-Ruiz and Lana-Renault, 2011), landscape and management point of view (Lasanta et al., 2015). However, despite the extensive cropland abandonment and the consequent revegetation process, and the time occurred after the first afforestation plans, few investigations have studied the consequences of secondary succession and afforestation in Mediterranean humid mountain environments related to soil properties. In recent years, some work has been published, analyzing the effects of land cover change, land abandonment and afforestation on soil properties (Pardini and Gispert, 2012; de Baets et al., 2013) on other Mediterranean subclimate types. In particular, there is evidence that secondary succession and afforestation leads to a significant change in the physical and chemical properties and biochemical soil cycles, but, there is no clear common pattern in the change observed. An overview of the main experimental studies investigating the effects of afforestations in soil properties in Mediterranean areas indicates that most of them were carried out in degraded/disturbed semi-arid areas (Cuesta et al., 2012; Laudicina et al., 2012) (the full dataset is included as online supplementary material). These studies had diverse objectives, mainly focused on the impact on physical and chemical soil properties after afforestation, and a few were also addressing C and N cycles.

A high variety of species were used, in the studies included in the dataset. It is important to note that conifers were the most common species. *Pinus halepensis* was often used, and it was one of the most important forest species in the Mediterranean basin (covering more than 25,000 km^2) applied for afforestation (Maestre and Cortina, 2004). This species was selected due to

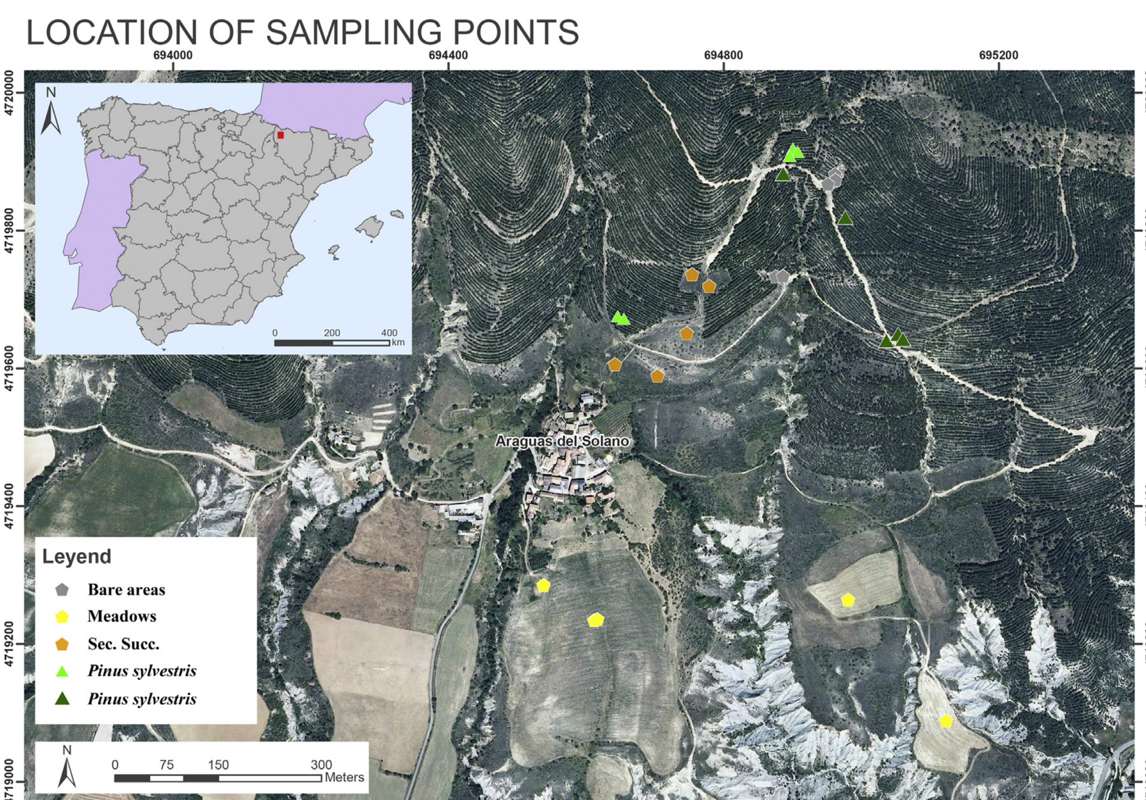

Fig. 1. Location of sampling points in the Araguás catchment. Location of the native natural forest is not shown in the Figure.

the low-technical requirements for nursery production (Pausas et al., 2004), and because it is a pioneer drought-resistant species that can survive in a wide range of conditions (Maestre et al., 2003). The overview supplied online, documents the high variability of soil properties changes after afforestation in Mediterranean areas. The discrepancies on observed results may be due to the tree density, and/or the degree of cover, planting technique, former land use as well as the period of time since planting.

Concluding from the findings above there is still considerable uncertainty about the effects of afforestation practices on soil property dynamics, and so far, no comparing study has been carried out for the effects of secondary succession and afforestation in Mediterranean humid mountain areas after cropland abandonment. Moreover, *P. nigra* and *P. sylvestris* afforestations were not considered in previous research.

Consequently, this paper aims to gain more insight into the discussion by exploring the following central research questions: (i) how do soil properties change after cropland abandonment in Mediterranean humid mountain areas? and (ii) what is the impact of secondary succession and afforestation on physical and chemical soil properties?

This leads to the following research hypotheses: (i) cropland abandonment followed by revegetation processes has an impact on important soil properties such as soil structure, texture and stability, bulk density, field capacity and C and N contents, and (ii) afforestation can accelerate the recovery of specific soil properties of abandoned cropland in comparison with natural secondary succession.

To test these hypotheses, we selected research areas consisting of 6 land covers (additionally 3 microsites in the afforestation areas were selected), which are representative of the present situations in the Mediterranean humid mountain area.

2. Materials and methods

2.1. Site description

A small catchment (Araguás catchment) in the Central Pyrenees (920–1105 m a.s.l.) was selected to carry out the soil sampling. The area was cultivated (in terraced fields) until the middle of the 20th century with cereal crops (some stone walls still remain). The area was abandoned in 1950 and most of it was afforested with *P. nigra* and *P. sylvestris* in 1965, although some areas underwent a process of natural secondary succession with *Genista scorpius, Juniperus communis, Rosa gr. canina* and *Buxus sempervirens*. The final result is a complex fine scale landscape mosaic (but with a homogenous

Fig. 2. Different land covers in the Araguás catchment.

lithology, climatology and former land use) in which afforestation patches alternate with dense and open shrubs, bare areas (that were not afforested) affected by sheet wash erosion, and actively used meadows (Figs. 1 and 2).

The bedrock is Eocene Flysch with alternating carbonate cemented sandstones and marl layers. The soils are stony and thin following centuries of cultivation and erosion. Soils have been modified, probably due to the past agricultural activities and subsequent afforestation techniques. The soils are classified as Leptic Calcaric Regosols with a silt loam texture (FAO, 2014).

The climate is sub-Mediterranean with oceanic and continental influences (Vicente-Serrano et al., 2007), and annual rainfall varies between 500 and 1000 mm (average annual rainfall approximates 800 mm). The average temperature is 10 °C (minimum −14 °C, maximum >30 °C).

2.2. Experimental design and sampling

Aerial photograph interpretation, topographic maps and field survey techniques were used to select 6 different land covers: bare lands, meadows, secondary succession, afforestation with *P. sylvestris* (hereafter PS) and afforestation with *P. nigra* (hereafter PN) as well as a nearby undisturbed natural (native) forest (Figs. 1 and 2). In the afforested areas (formerly cultivated lands) three specific microsites per plot were identified: the escarpment area (es), the terrace sector (te) and the trunk/stem sector (st) as these sites were strongly altered (terraced) while being afforested. For the native forest site two microsites were sampled (close to the stem and below the tree, under the canopy (hereafter open)). For each of the 6 land covers and the different microsites five plots (5 m × 5 m) were selected, all with similar topographic conditions (slope and exposition).

An extensive soil sampling was carried out in September 2014. We systematically collected 5 top soil samples (after the litter of the ectorganic horizon had been removed) (0–10 cm) and 3 deep soil samples (10–20 cm) per plot at one of the plot diagonals (depth soil samples were not collected in the bare areas due to the presence of parent material). 5 subsamples were selected in each plot and depth (total 345 samples), and were combined into one single soil composite sample per depth and per plot. In total 85 composite samples were collected. Three core samples (per microsites and depth) were taken with the help of steel cylinders to determine bulk density values in the laboratory (63 samples). Surface mechanical resistance (defined as the capacity of a particular soil, in a particular condition, to resist an applied force measurements of surface) were measured using a pocket penetrometer (Geotester G. Weber).

2.3. Laboratory analysis

The soil samples were air dried and passed through 2 mm mesh sieve in the laboratory (remaining roots and stones were carefully removed). The soil properties analysed were as follows: (i) field bulk density (BD) which was estimated from undisturbed cores that were oven-dried at 105 °C for 24 h (Blake and Hartge, 1990); (ii) pH and electrical conductivity (EC), which were measured in a deionized water suspension (1:2.5) using a pH meter and a conductivity meter; (iii) total carbon (C_{total}) and total nitrogen concentrations (N), which were determined by dry combustion using an elemental analyser (Vario El Cube Elementar); (iv) carbonate content ($CaCO_3$) which was determined using the Wesemael method (van Wesemael, 1955) from which also the total inorganic carbon was calculated (C_{inorg}); (v) organic carbon (C_{org}) was calculated by subtraction of total inorganic carbon (C_{inorg}) from the C_{total}; (vi) soil organic carbon (SOC) and nitrogen (TN) stocks were expressed in Mg ha^{-1} (calculated weighting each C_{org} and N value by the respective depth and bulk density); (vii) organic matter (OM), which was determined using the loss on ignition method (at 375 °C); (viii) grain size distribution which was determined using a particle size analyser (Micromeritics, Sedi-Graph 5100, Nocross, USA); (ix) organic phosphorus (P), which was determined through the difference in phosphorus in ignited (at 500 °C for four hours) and non-ignited samples (samples were extracted with sulphuric acid and the amount of phosphorus was then established colorimetrically) (ignition method as described by Kuo (1996)); (x) soil hydraulic properties (saturated soil moisture (SAT), field capacity (FC) and wilting point (WP)) were estimated using pedotransfer functions (from texture data and organic matter values; Rawls et al., 1992); and (xi) the CN ratio was calculated using C_{org} and TN.

Aggregate stability has been used as an indicator of soil erodibility and ecosystem degradation degree (Cerdà, 1998). The aggregate stability was determined in the laboratory using the drop Test (Counting the Number of Drops) (Imeson and Vis, 1984). Aggregates of 4–4.8 mm diameter were selected by dry sieving. The test was carried out with dry and wet aggregates that were pre-wetted at pF1 for 24 h before commencing the analysis. 20 aggregates per microsite and moisture condition were randomly selected, and we counted the number of drop impacts required to disrupt the aggregate sufficiently to pass through the 2 mm sieve.

Table 1
F values and significance (p) of ANOVA analysis for all properties in all soil samples for the different microsites (escarpment, terrace and stem) in the *P. sylvestris* and *P. nigra* land covers.

P. sylvestris		C_{org}	C_{inorg}	N	SOC	TN	CN ratio	OM	pH	EC	$CaCO_3$	Clay	Sand	Silt	P	BD	FC
Microsites	F	1.587	0.160	0.449	0.395	0.622	0.465	1.524	5.056	2.123	0.510	1.925	0.250	0.147	0.415	0.707	2.018
	p	0.228	0.853	0.645	0.681	0.546	0.634	0.241	*0.016*	0.145	0.608	0.180	0.782	0.864	0.666	0.510	0.176
Soil Depth	F	15.267	0.159	4.679	3.658	15.078	11.264	15.875	5.138	13.268	7.333	0.579	2.049	2.310	3.094	3.653	6.076
	p	*0.001*	0.221	*0.044*	0.075	*0.001*	*0.003*	*0.001*	*0.034*	*0.001*	*0.013*	0.458	0.172	0.148	0.092	0.075	*0.028*
Microsites × soil depth	F	2.463	0.772	0.473	1.109	1.736	1.781	2.302	2.548	2.094	1.835	1.038	0.456	0.423	0.654	2.606	3.320
	p	0.123	0.596	0.631	0.397	0.232	0.223	0.141	0.115	0.169	0.212	0.457	0.799	0.821	0.667	0.110	0.064
P. nigra		C_{org}	C_{inorg}	N	SOC	TN	CN ratio	OM	pH	EC	$CaCO_3$	Clay	Sand	Silt	P	BD	FC
Microsites	F	0.732	0.012	0.298	0.997	0.317	0.399	0.741	2.425	9.860	0.045	1.952	0.588	0.147	3.889	0.068	1.351
	p	0.501	0.998	0.752	0.388	0.734	0.679	0.497	0.130	*0.003*	0.956	0.184	0.571	0.865	0.050	0.935	0.296
Soil Depth	F	4.109	0.603	1.956	0.007	3.955	0.453	4.353	1.696	0.183	0.160	0.650	0.627	2.522	2.317	10.257	5.354
	p	0.065	0.452	0.179	0.936	0.070	0.513	0.059	0.186	0.676	0.696	0.436	0.444	0.138	0.154	*0.008*	0.059
Microsites × soil depth	F	0.735	0.538	0.665	1.042	1.235	0.401	0.803	0.129	2.321	0.320	0.301	0.398	0.596	1.947	1.276	0.976
	p	0.500	0.597	0.527	0.373	0.325	0.679	0.471	0.880	0.141	0.732	0.745	0.680	0.566	0.185	0.314	0.405

C_{org}: organic carbon; C_{inorg}: inorganic carbon; N: nitrogen content; SOC: soil organic carbon stock; TN: nitrogen stocks; OM: organic matter; EC: electrical conductivity; $CaCO_3$: carbonate content; P: organic phosphorus; BD: bulk density; FC: field capacity.
p in italics are significantly different at $p < 0.05$.

2.4. Statistical analysis

All data were tested for normal distribution for all measured properties using the Shapiro-Wilk and Chi-square tests. Homogeneity of variances was tested using Levene's test.

Analysis of variance, a two-way ANOVA, was used to compare the differences among microsites and depths (Table 1) and the land covers and depths (Table 2). A posteriori, Tukey post-hoc tests were used to confirm where the differences occurred between groups (Table 3).

To determine the differences for the aggregate stability results, due to the non-normality of the data, the non-parametric Kruskal-Wallis test was used. In all cases, we considered differences to be statistically significant at $p < 0.05$ (Table 4).

Principal component analysis (PCA) was also performed to determine first correlations among the measured variables and to elucidate major variation patterns in terms of microsites. The position of different soil samples in the factorial plane will be shown using regression statistical techniques. All statistical analysis was carried out using SPSS Statistics 20 and R software (version 3.2.3).

2.5. Soil quality index assessment

Soil-quality is in growing demand, thus a standard set of procedures to assign a soil quality index (SQI) have been used. The indexing technique assessed here follows that proposed by Armenise et al. (2013). Soil physical and chemical parameters were measured, screened through PCA, normalized and then integrated into a weighted-additive SQI.

Eight components were defined, although only the first 3 principal components (PCs) were kept. These 3 PCs explained 76.06% of the total variation. The PC1 explained 56.52% of the variance and the PC2 explained 10.63%.

Later, correlation analysis was used to find out redundant variables within each PC and a reduction in variables could be obtained. The highest weighted variables under PC1 were all significantly correlated, and we selected C_{total}, OM and SAT, considering the key role that these variables play in determining the quality of soils. Under PC2 clay content and BD were selected, and under PC3 EC was selected. The final minimum data set (MDS) to be included in the index comprised: C_{total}, OM, SAT, clay content, BD and EC.

Non-linear scoring functions were used to transform the MDS soil properties to a value between 0 and 1 (Armenise et al., 2013); the "more is better" functions were used for C_{total} and OM; the "optimum function" was used to score clay content, EC and SAT; and the "less is better" to BD. Weights were assigned to the MDS indicators using the PCA outcomes and were equal to the percentage of variance explained, standardised to unity. C_{total}, OM and SAT were selected for PC1 so the full weight (0.57) was divided between these three parameters (0.19 each one); clay and BD were selected for PC2 so the full weight (0.11) was divided; and the full weight for PC3 (0.9) was assigned to EC.

The final SQI was as follows:

$$SQI = 0.24 \times S_{Ctotal} + 0.24 \times S_{OM} + 0.24 \times S_{sat} + 0.08\, S_{clay} + 0.08 \times S_{BD} + 0.12 \times S_{EC}$$

where S was the score for the subscripted variable and the coefficients were the weighting factors.

3. Results

3.1. Physical and chemical soil properties

Table 1 shows the values of two-way ANOVA analysis for the microsites in PS and PN. Microsites did not have significant effects on soil variables. As no differences were found between microsites, we combined the 3 microsites as one site in the subsequent analysis (Tables 2 and 3).

Our results from two-way ANOVA showed that some soil properties were significantly different depending on land cover and depth (Table 2). Land cover was the factor that had the greatest significant effect on soil samples.

Significant differences appeared for C_{org}, C_{inorg}, N content, SOC and TN stock, CN ratio, OM, silt, P and BD (Table 2). The highest C_{org} concentrations were obtained in the natural forest and PN, and the lowest value was obtained from the 0–10 cm layer in the bare area (Table 3). Significant differences were observed between PN and natural forest and the different land covers. The highest SOC stocks were recorded in the natural forest. Significant differences were observed between natural forest and the other land covers, and between bare areas and the other land covers. Significant differences were also observed between different depths in the secondary succession, afforestation and natural forest sites (Table 3).

The C_{inorg} concentration was closely associated with land cover. The highest concentration was recorded in bare and the lowest in the natural forest and PN (Table 3). Only significant differences were observed between samples from natural forest and the different land covers at 0–10 cm.

Significant differences related to N concentrations and stocks were also found (Table 3). Significant differences related to the CN ratios were observed between afforested covers and bare areas, meadows and secondary succession sites (Table 3).

The highest pH values were observed at bare sites (Table 3) and significant differences between land covers were observed. Related to EC, no significant differences were found.

The concentration of P was closely associated with the land cover. The highest P was recorded in the meadows, and the lowest

Table 2
F values and significance (p) of ANOVA analysis for all properties in all soil samples. Tukey post-hoc test are shown in Table 3 and were used to confirm where the differences occurred between groups.

		C_{org}	C_{inorg}	N	SOC	TN	CN ratio	OM	pH	EC	Clay	Sand	Silt	P	BD	FC
Land cover	F	9.921	14.524	1.801	1.923	2.662	11.184	10.114	3.776	0.628	0.101	3.745	5.453	6.103	17.840	0.223
	p	*0.000*	*0.000*	*0.037*	*0.029*	*0.041*	*0.000*	*0.000*	*0.011*	0.680	0.991	*0.011*	*0.002*	*0.001*	*0.000*	0.949
Soil Depth	F	10.964	0.496	1.235	2.45	0.377	1.630	11.241	1.22	0.737	0.826	0.065	0.888	5.049	17.562	0.055
	p	*0.003*	0.488	*0.043*	*0.624*	0.544	0.211	*0.003*	0.730	0.399	0.732	0.801	0.355	0.070	*0.000*	0.816
Land cover × soil depth	F	3.876	0.091	1.958	0.388	0.644	3.403	3.897	0.941	0.270	0.448	0.544	0.973	0.958	0.808	0.106
	p	*0.014*	0.984	0.076	0.816	0.635	*0.020*	*0.014*	0.457	0.894	0.773	0.705	0.440	0.448	0.532	0.979

C_{org}: organic carbon; C_{inorg}: inorganic carbon; N: nitrogen content; SOC: soil organic carbon stock; TN: nitrogen stocks; OM: organic matter; EC: electrical conductivity; P: organic phosphorus; BD: bulk density; FC: field capacity.
p in italics are significantly different at $p < 0.05$.

Table 3
Mean and standard deviations of the studied soil properties. Soil characteristics resulting from former land covers, revegetation processes (secondary succession and afforestation) (PS = *Pinus sylvestris* and PN = *Pinus nigra*) and natural forest conditions.

	Soil depth (cm)	Bare areas	Meadows	Secondary succession	PS	PN	Natural forest
C_{org} (%)	0–10	0.7 ± 0.1^{a}	2.1 ± 0.7^{a}	2.4 ± 0.5^{Aa}	3.1 ± 0.8^{Aab}	3.8 ± 0.8^{ab}	7.8 ± 2.3^{Ac}
	10–20		2.4 ± 1.6	1.5 ± 0.3^{B}	1.7 ± 0.2^{B}	2.8 ± 0.1	3.3 ± 1.2^{B}
C_{inorg} (%)	0–10	5.3 ± 0.1^{a}	4.2 ± 0.4^{a}	4.4 ± 0.3^{a}	4.3 ± 0.4^{a}	4.0 ± 0.4^{a}	2.8 ± 0.8^{b}
	10–20		4.0 ± 0.4^{a}	4.3 ± 0.2^{a}	4.5 ± 0.1^{a}	3.7 ± 0.6^{ab}	2.7 ± 0.5^{b}
N (%)	0–10	0.06 ± 0.001^{a}	0.24 ± 0.09^{b}	0.24 ± 0.05^{Ab}	0.22 ± 0.05^{Ab}	0.24 ± 0.04^{Ab}	0.48 ± 0.09^{Ac}
	10–20		0.19 ± 0.07^{a}	0.15 ± 0.03^{Bab}	0.14 ± 0.03^{Bab}	0.20 ± 0.03^{Ba}	0.29 ± 0.08^{Bac}
SOC ($Mg\,ha^{-1}$)	0–10	12.7 ± 0.6^{a}	26.4 ± 10.1^{b}	26.6 ± 7.0^{b}	28.1 ± 6.5^{b}	29.4 ± 5.8^{b}	35.0 ± 9.8^{c}
	10–20		31.5 ± 26.2	21.8 ± 3.0	21.9 ± 0.8	29.7 ± 4.8	32.4 ± 12.3
TN ($Mg\,ha^{-1}$)	0–10	1.1 ± 0.1^{a}	3.0 ± 1.2^{b}	2.7 ± 0.8^{b}	2.2 ± 0.9^{b}	1.7 ± 0.5^{b}	2.1 ± 0.6^{b}
	10–20		2.5 ± 1.3	2.1 ± 0.2	1.8 ± 0.1	2.1 ± 0.4	2.5 ± 0.6
CN ratio	0–10	11.2 ± 1.8^{a}	8.8 ± 0.5^{Aa}	10.2 ± 1.3^{a}	14.2 ± 1.2^{Aabc}	15.6 ± 1.6^{bc}	15.8 ± 2.5^{bc}
	10–20		11.6 ± 3.3^{B}	10.3 ± 0.8	12.2 ± 0.7^{B}	14.2 ± 0.4	12.8 ± 2.2
OM (%)	0–10	1.4 ± 0.2^{a}	4.1 ± 0.3^{a}	4.7 ± 0.7^{Aa}	6.1 ± 1.7^{Aa}	7.6 ± 1.4^{Aab}	15.5 ± 4.7^{Ac}
	10–20		4.7 ± 3.2	3.0 ± 0.5^{B}	3.4 ± 0.4^{B}	5.5 ± 0.1^{B}	6.6 ± 2.3^{B}
pH	0–10	7.96 ± 0.04^{a}	$7.35 \pm 0.09\ ^{b}$	7.45 ± 0.07^{Ab}	7.4 ± 0.08^{b}	7.4 ± 0.05^{b}	7.0 ± 0.04^{c}
	10–20		7.39 ± 0.23	7.61 ± 0.04^{B}	7.55 ± 0.08	7.44 ± 0.01	6.43 ± 1.5
EC ($\mu S\,cm^{-1}$)	0–10	149 ± 5	336 ± 145	313 ± 106	333 ± 40^{A}	370 ± 80	284 ± 66
	10–20		248 ± 82	297 ± 130	255 ± 24^{B}	309 ± 30	280 ± 94
Clay (%)	0–10	24	31 ± 5	31 ± 3	30.1 ± 2	31 ± 2.3	44 ± 3
	10–20		31 ± 2	33 ± 3	31 ± 2	32 ± 2	38 ± 8
Sand (%)	0–10	10	16 ± 5	12 ± 5	17 ± 4	19 ± 5	14 ± 4
	10–20		17 ± 7^{ab}	9 ± 5^{ab}	13 ± 4^{ab}	21 ± 5^{ac}	10 ± 2^{ab}
Silt (%)	0–10	66	53 ± 5^{a}	57 ± 3^{a}	53 ± 4^{a}	50 ± 4^{a}	43 ± 1^{b}
	10–20		52 ± 5^{a}	58 ± 2^{ab}	56 ± 2^{ab}	47 ± 3^{a}	42 ± 10^{ac}
P ($mg\,kg^{-1}$)	0–10	46.9 ± 46.1^{a}	211.5 ± 103.8^{b}	118.6 ± 89.5^{ab}	96.7 ± 17.7^{ab}	129.4 ± 16.4^{ab}	189.0 ± 31^{ab}
	10–20		$119\ .7\ 0.7 \pm 43.0^{a}$	66.9 ± 13.3^{a}	78.2 ± 11.7^{ab}	110.2 ± 10.0^{a}	141.4 ± 29.9^{ac}
BD ($g\,cm^{-3}$)	0–10	1.73 ± 0.1^{a}	1.28 ± 0.2^{Aa}	1.12 ± 0.2^{a}	1.17 ± 0.4^{ab}	0.71 ± 0.2^{Abc}	0.43 ± 0.1^{Ac}
	10–20		1.48 ± 0.1^{Ba}	1.58 ± 0.1^{a}	1.42 ± 0.1^{a}	1.07 ± 0.2^{Bb}	0.79 ± 0.2^{Bb}
FC	0–10	0.37	0.46 ± 0.06	0.47 ± 0.04	0.50 ± 0.04^{A}	0.55 ± 0.09	0.83 ± 0.15
	10–20		0.48 ± 0.09	0.24 ± 0.02	0.24 ± 0.0^{B}	0.27 ± 0.02	0.32 ± 0.05

Note: Means with the different lower case letter superscripts within a row are significantly different at 0.05 level of significance ($p < 0.05$)
Means with the different upper case letter superscripts within a column are significantly different at 0.05 level of significance ($p < 0.05$)
C_{org}: organic carbon; C_{inorg}: inorganic carbon; N: nitrogen content; SOC: soil organic carbon stock; TN: nitrogen stocks; OM: organic matter; EC: electrical conductivity; P: organic phosphorus; BD: bulk density; FC: field capacity.

Table 4
Mean and standard deviations of the number of drops (aggregate stability) (0–10 and 10–20 cm). Soil characteristics resulting from former land covers and microenvironment induced by revegetation processes (secondary succession and afforestation).

Number of drops		DRY	WET
Bare	0–10	26 ± 10	26 ± 12
	10–20	–	–
Meadows	0–10	65 ± 32	39 ± 27
	10–20	47 ± 28	51 ± 34
Secondary succession	0–10	60 ± 25	52 ± 27
	10–20	80 ± 31	59 ± 34
PS_Es	0–10	52 ± 25	66 ± 32
	10–20	78 ± 30	58 ± 24
PS_Te	0–10	111 ± 55	71 ± 36
	10–20	65 ± 32	68 ± 40
PS_St	0–10	98 ± 50	107 ± 54
	10–20	71 ± 29	101 ± 46
PN_Es	0–10	90 ± 42	87 ± 49
	10–20	102 ± 34	91 ± 46
PN_Te	0–10	75 ± 42	74 ± 26
	10–20	72 ± 30	52 ± 31
PN_St	0–10	100 ± 37	111 ± 62
	10–20	98 ± 52	92 ± 43
Forest cover	0–10	149 ± 37	170 ± 45
	10–20	90 ± 42	126 ± 61
Forest stem	0–10	166 ± 23	174 ± 37
	10–20	111 ± 18	127 ± 62

(PS = *Pinus sylvestris* and PN = *Pinus nigra*; Es = escarpment; Te = terrace; St = stem).

in the bare soil (Table 3). Significant differences were recorded between bare and meadows.

Land cover and soil depth did not significantly affect the amount of clay and the FC values (Table 3).

3.2. Soil quality index assessment

The effects of land cover, cropland abandonment and secondary succession and afforestation practices were evaluated by computing a SQI (see Section 2.5). The SQI was applied to summarize all the obtained results and to test if there were differences between the different land covers. Considering the 19 physical and chemical soil variables we carried out a statistical analysis. Fig. 3 showed the position of the soil samples in the factorial plane. Even though a successful discrimination was not observed, some small differences could be highlighted between soil samples, especially the bare samples.

MDS indicators using the PCA outcomes were C_{total}, OM, SAT, BD and EC. Among the studied land covers, the SQI ranged from 0.19 to 0.34. The lowest value was obtained for bare areas, and the highest values were obtained in the natural forest (0.62) and PN (Fig. 4). Significant differences were only observed between bare areas and natural forest and the other land covers.

3.3. Aggregate stability

The results of the aggregate stability showed a high variation. Bare soils had the least stable aggregates both in dry and wet conditions. On average, soils beneath natural forest showed the

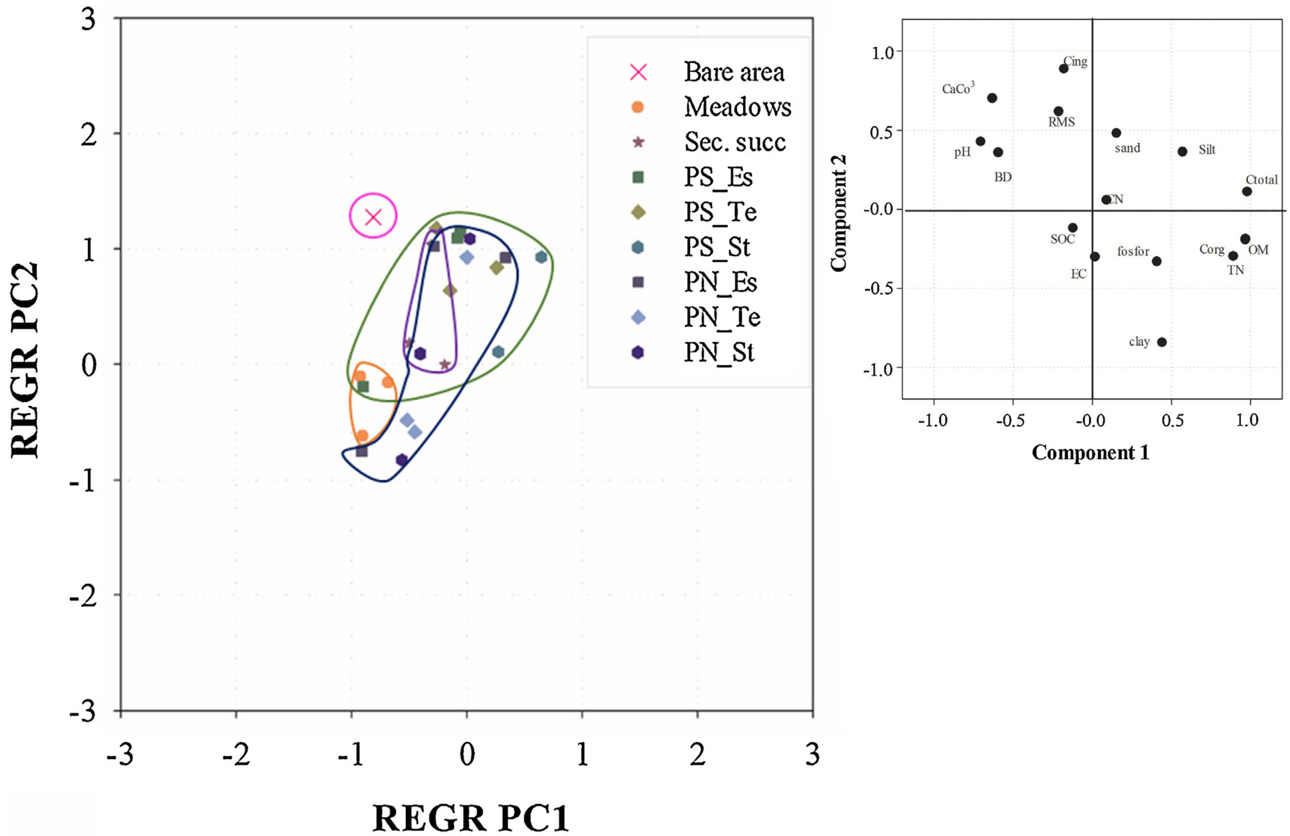

Fig. 3. Factorial analysis and distribution of soil samples upon the 1–2 factorial plane.

most stable aggregates. Then, afforestation sites showed the most stable in both situations (Table 4). Significant differences were observed in dry conditions between aggregates from bare areas and all the land covers. In wet conditions differences were observed between: (i) bare sites and all the afforestation covers, (ii) meadows and PN and PS, and (iii) secondary succession and PN and PS. Only significant differences between dry and wet aggregates were observed for meadows.

4. Discussion

4.1. Land cover and soil properties

From the 1950s, the process of cropland abandonment and the following establishment of vegetation in the Mediterranean mountains aimed at re-converting abandonment lands into forest areas. Our study demonstrated that land cover has a significant

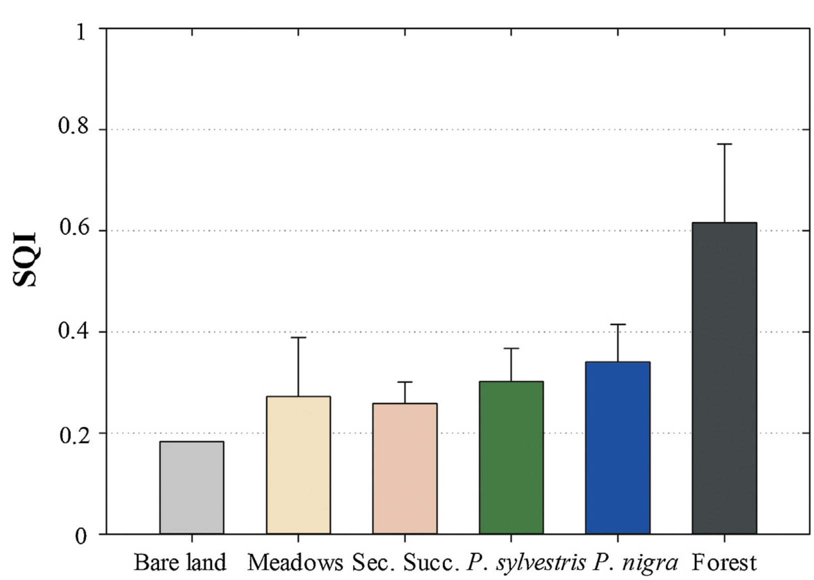

Fig. 4. Index value (SQI) calculated based on Armenise et al. (2013) for the different land covers.

effect on physical and chemical soil variables, for both the top- and subsoil, although the differences for the soil variables between land covers were greatest in the topsoil. A large number of studies worldwide have demonstrated that land cover changes affect soil properties, and that this is particularly true in the Mediterranean region (Zornoza et al., 2009). However, there is no agreement in the literature in relation to the effect of secondary succession and afforestation on soil properties. Many studies showed that afforestations improve soil properties. To the contrary, our results showed that soil changes after cropland abandonment are limited, even if afforestation practices were carried out. Afforestation can improve soil properties, aggregate stability and carbon concentrations and contents when compared to neighbouring bare soils. Caracava et al. (2002) reported improvements on physical soil properties after afforestation of a semiarid site with *P. halepensis*, and Yuksek and Yuksek (2011) concluded that some soil properties improved approximately 10 years after plantation. Less is known about how soil properties change after cropland abandonment in humid mountains under secondary succession and afforestation practices. Our results indicated that after more than 50 years of cropland abandonment there are no significant differences between secondary succession and afforestation sites, neither with meadows.

The C_{org} concentration was closely associated with land cover and depth, recording the highest values at 0–10 cm in the PN and natural forest. There is no agreement in the literature in relation to the effects of afforestation in soil carbon. Hoogmoed et al. (2012) conducted a hierarchical Bayesian meta-analysis of published data to study the effects of afforestation of pastures on soil carbon and nitrogen stocks under Mediterranean climate. They found no evidence for substantial changes in SOC, TN or CN ratio across three decades of afforestation. Bayramin et al. (2009) showed that the differences of the C_{org} between grassland and *P. nigra* were insignificant, indicating the ineffectiveness of pine plantations on changing the C_{org}. On the other hand, it seems evident that significant changes in C_{org} occur when degraded areas were afforested (Maestre et al., 2003). Secondary succession following land abandonment also determined the C_{org} concentration, and in general, in Mediterranean mountains an increase in C_{org} is reported due to a slow increase in the input of organic matter (Cammeraat et al., 2005; Lesschen et al., 2008).

The amount of N differed between bare and meadows and revegetated areas. Plants with high growth rates, such as herbaceous vegetation that usually proliferates on abandoned cropland, show high N concentration, and the legumes plants have N-fixing capacity, which increase soil N content (Hooper and Vitousek, 1998).

The highest P was recorded in the meadows. It has been demonstrated that agricultural land use increases the concentration of P due to the application of fertilizers, and this effect usually persists for a long time after cropland abandonment (Smal and Olszewska, 2008). Our results showed that there were no differences between meadows and secondary succession and afforested areas, probably showing the persistent effects of fertilizer.

All land covers were characterized by a similar particle size distribution with silt as the dominant fraction. Only significant differences were recorded in silt content in the natural forest and some differences in clay content. Other studies have reported similar results in different environments (Khresat et al., 2008). Laudicina et al. (2012) evaluated the effects of plant cover on soil properties of four afforested soils in central Sicily and they found that soil texture and pH were not affected after 60 years of afforestation.

To evaluate the influence of afforestation practices and mechanical soil preparation on soil properties, we recognized three different microsites. Oxen were used to carry out afforestation practices: terraces are not wide, and the escarpments are not too high, and sometimes it was difficult to identify these microsites after 50 years of afforestation. Our results demonstrated that the impact of disturbance by afforestation mechanical preparation is difficult to discern and no significant differences were observed between the microsites, which was also reported by Chaparro et al. (1993); Ruiz-Navarro et al. (2009).

The influence of land cover on soil erosion vulnerability was studied by means of aggregate stability measurements: big differences between land covers were found. Vegetation succession after cropland abandonment increases aggregate stability (Cammeraat and Imeson, 1998; Chrenkova et al., 2014). Our results demonstrated that always the most unstable sites were those with bare soils. The vegetated soils had the stronger aggregates, especially the afforestation sites and natural forest. Vegetation generally increased soil organic matter and soil porosity, reducing bulk density and favouring a better environment to biological activity, which increased aggregate stability (Cerdà, 1998). Caracava et al. (2002) also showed that afforestation increased aggregate stability in semiarid areas. In that sense, afforestation practices are a proven tool for the improvement of soil structure and mitigating the risk of erosion.

This research studied a nearby undisturbed natural forest, as reference ecosystem. In general, most authors reported losses in soil quality when comparing afforestation with natural forest areas (Fernández-Ondoño et al., 2010). Our analysis showed that the native forest presented better soil quality and had much higher SOC levels than secondary succession and afforested areas, probably due to the characteristics of the vegetation (type, age, and biomass), litter accumulation and soil formation (acidification, soil structure development and bioturbation). Hoogmoed et al. (2012) concluded that SOC in soils under afforestation were significantly lower than those under remnant forests, which is also our conclusion. The differences found with respect to the native forests appear to indicate that the afforested soils have by far not yet reached their maximum potential to store SOC.

4.2. Secondary succession versus afforestation: management and implications

Our results showed that there are no differences in soil properties and soil quality rating, between the two types of revegetation restoration studied. Regarding SOC which is considered to be the most important indicator for soil quality, no significant differences were observed. Soil data obtained in this study suggested that for the time being (around 50 years), the introduction of *P. sylvestris* and *P. nigra* in Mediterranean humid mountain areas after cropland abandonment has not substantially improved soil conditions versus secondary succession, probably because of low tree productivity and growth associated with lithology constraints and former conditions.

In general, afforestation polices in Mediterranean mountain areas pursued economic and environmental purposes: (i) achieve self-sufficiency in the supply of pulp and paper, and (ii) regulate the hydrological cycle, in order to reduce flood frequency and magnitude. Regarding economic purposes, results are scarce, because so far, wood has not been obtained; with respect to water, hydrological studies have demonstrated that afforestation reduces the water yield and the number of floods, when compared to non-vegetated areas and abandoned lands (Nadal-Romero et al., 2016). García-Ruiz et al. (2015) showed that the annual runoff coefficient in the afforestation catchment is lower compared with a neighbouring catchment characterized by secondary succession after cropland abandonment (0.21 and 0.27 respectively). Moreover, afforestation practices failed in the control of extreme hydrological events (Nadal-Romero et al., 2016). Finally, the present study has demonstrated that after 50 years of cropland abandonment, soil properties and consequently soil quality is similar in secondary succession patches compared to afforested areas. So, a global and highly relevant question emerges from this research: How should we proceed: secondary succession or afforestation practices?

The effects of cropland abandonment and afforestation practices on soil properties should be considered in the design of future forest restorations. Afforestation is increasingly viewed as an environmental restorative land cover change prescription and is considered to be one of the most efficient carbon sequestration strategies currently available. Given the large quantity of CO_2 that soils release annually, it is important to understand disturbances in vegetation and soils resulting from land cover changes and cropland abandonment. To complement this study, further research related to soil carbon sequestration will be carried out to test the effect of cropland abandonment and consequent revegetation processes on SOC stocks.

5. Conclusions

This study has provided novel information on the effects of cropland abandonment and secondary succession and afforestation practices on soil properties in a mountain humid Mediterranean area. Our findings demonstrated that contrary to our hypothesis, afforestation did not accelerate the recovery of soil properties and soil quality in comparison with secondary succession.

The following conclusions can be made:

(i) Soil recovery after cropland abandonment was slow even if afforestation was carried out.
(ii) No significant differences with regard to soil quality improvements were observed between areas under secondary succession and afforestation.
(iii) Afforestation improved soil properties, SOC and aggregate stability when compared to bare soils.
(iv) Land cover and soil depth had significant effects on soil properties. The effect of land cover were in most cases confined to the topsoil.
(v) Vegetation growth and especially afforestation promotes the formation of more stable aggregates.
(vi) A well-developed soil quality index, based on statistical analysis, suggested that natural forest presented the highest soil quality, followed by *P. nigra* areas. The significant differences found with respect to the native forest appear to indicate that the afforested soils have not yet reached their maximum potential as SOC sink.

The effects of afforestation practices on soil properties should be considered in the design of future forest restorations. The results of this research can be useful for forest management and environmental planners in order to decide the best practices after land abandonment.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.05.003.

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